The Why, What, Where of the Long Baseline Neutrino Experiment

INPA, Lawrence Berkeley National Lab, 03/01/2013

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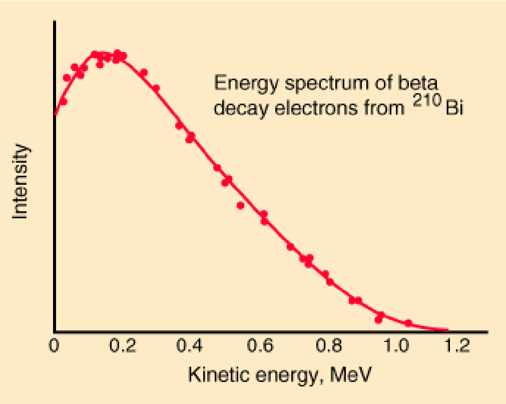
Outline

A BRIEF HISTORY OF NEUTRINOS

Neutrino Conception

Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



G.J Neary, Proc Phys. Soc., A175, 71 (1940)

Neutrino Conception

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen proposes that a neutrally charged "neutron" with a mass "$<$ 0.01 proton mass" is emitted in beta-decays.

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

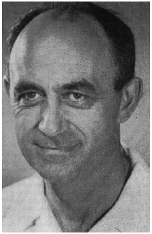
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

1932: James Chadwick discovers the neutron - its too heavy - cant be Pauli's particle

James Chadwick

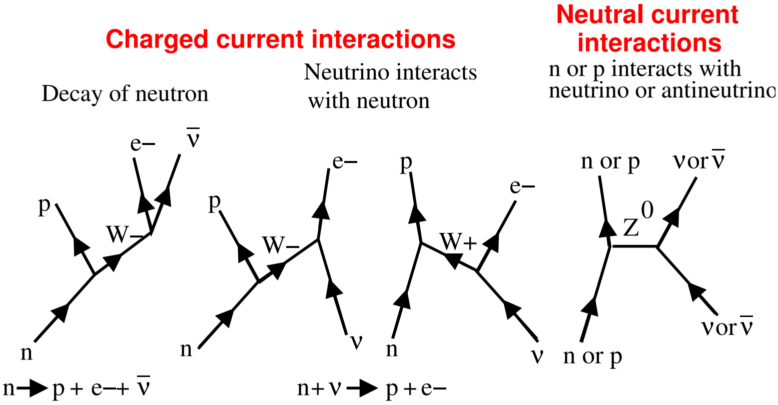
Solvay Conference, Bruxelles 1933: Fermi proposes to name Pauli's particle the "neutrino".



Enrico Fermi

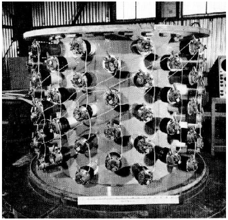
The Theory of Weak Interactions

$\geq$ **1933:** **Development of the theory of weak interactions and beta decay**



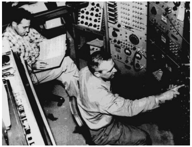
Finding Neutrinos...

1950's: Fred Reines at Los Alamos and Clyde Cowan mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

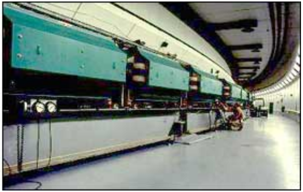
1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV + T_e^+)
3. $n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$ ($\tau = 5\mu s$).



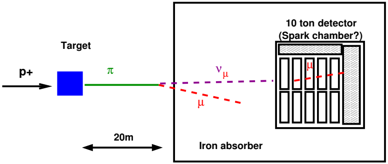
Neutrinos first detected using a nuclear reactor!

Neutrinos have Flavors

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu\nu_x$



The AGS



Making ν's

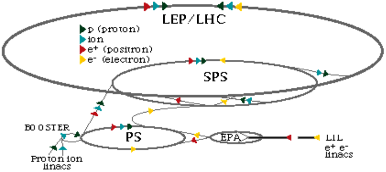
Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

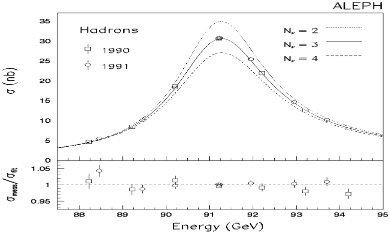
The first accelerator neutrino experiment was at the AGS.

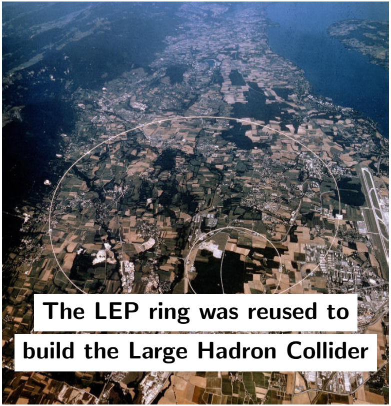
Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- particle colliders. $\mathbf{N_\nu = 2.984 \pm 0.008}$

The LEP e^+e^- collider at CERN, Switzerland

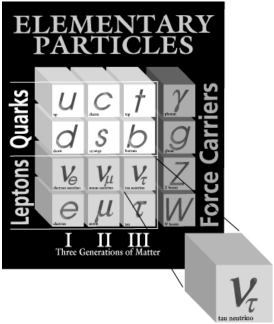




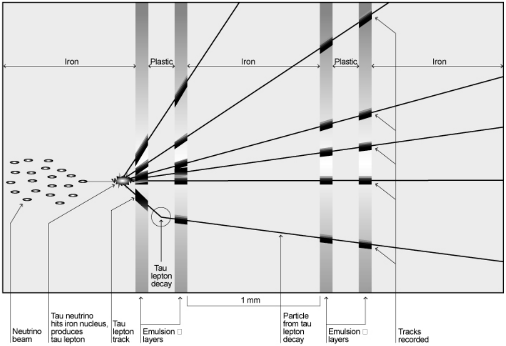


Direct Observation of ν_τ

July 20, 2000. The DONUT experiment finds evidence for the 3rd neutrino:



Detecting a Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

Standard model: 3rd neutrino is the partner of the τ lepton

NEUTRINO MIXING AND OSCILLATIONS

Neutrino oscillations

1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

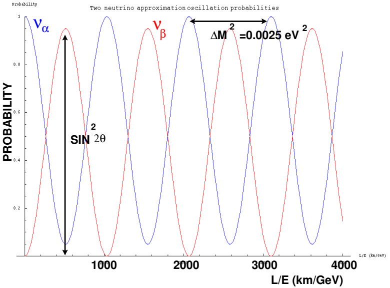
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

Ray Davis

1. $\nu_e^{sun} + ^{37}CL \rightarrow e^- + ^{37}Ar, \ \tau(^{37}Ar) = 35$ days.
2. **Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.**

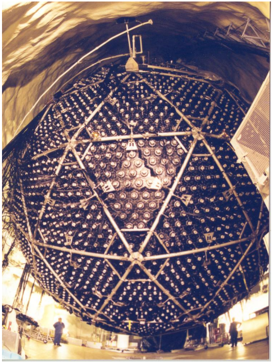
Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Solar ν_e disappearance $\Rightarrow$

first experimental hint of oscillations

SNO Experiment: Solar $\nu_e \longrightarrow \nu_x$ Measurments

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:



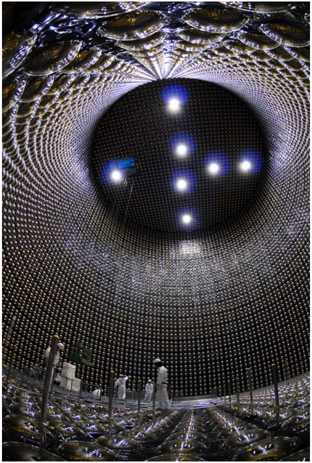
$$1)\ \nu_e + d \longrightarrow e^- + p + p\ \text{(CC)}.$$
$$2)\ \nu_x + d \longrightarrow p + n + \nu_x\ \text{(NC)}.$$
$$3)\ \nu_x + e^- \longrightarrow e^- + \nu_x\ \text{(ES)}.$$

SNO measured:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

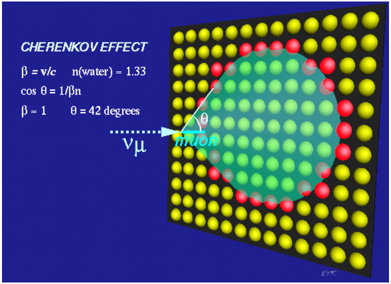
All the solar ν's are there but ν_e appears as ν_x!

The Super-Kamiokande Experiment. Kamioka Mine, Japan

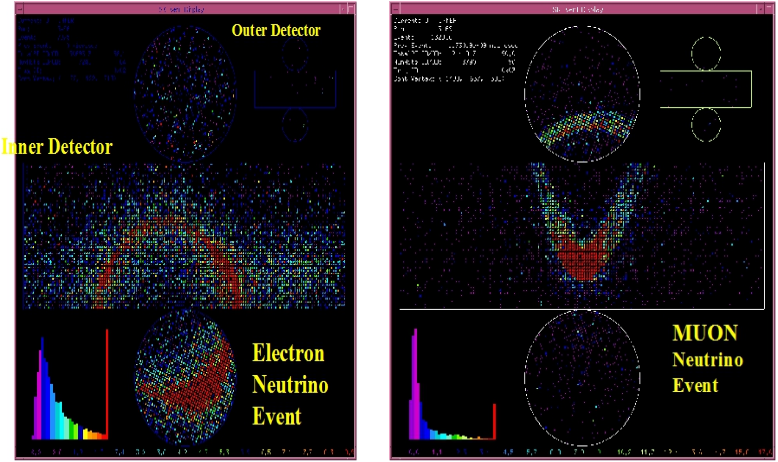


50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

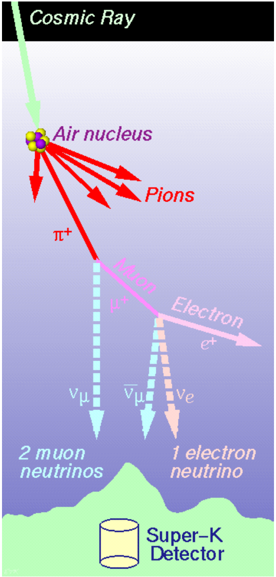
Neutrinos are identified by using CC interaction $\nu_{\mu,e} \rightarrow e^{\pm}, \mu^{\pm}X$. The lepton produces Cherenkov light as it goes through the detector:

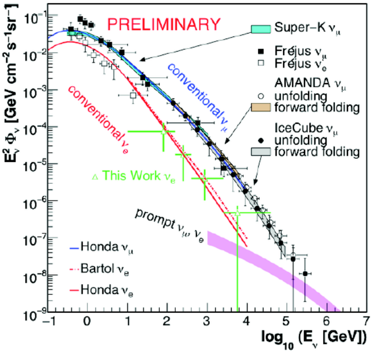


The Super-Kamiokande Experiment. Kamioka Mine, Japan



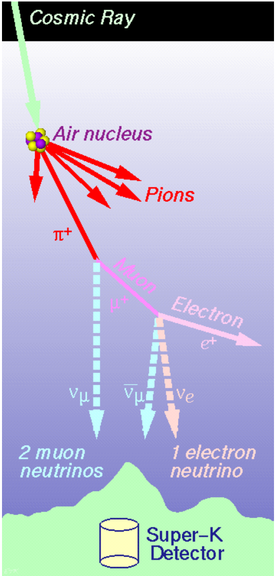
Atmospheric Neutrino Oscillations: $\nu_\mu, \nu_e, \bar{\nu}$

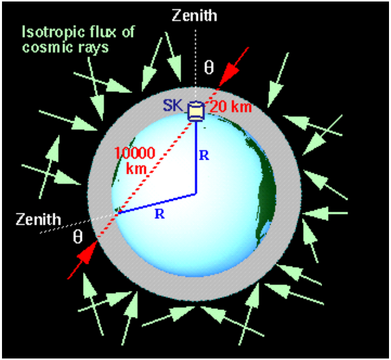




Many decades in E

Atmospheric Neutrino Oscillations: $\nu_\mu, \nu_e, \bar{\nu}$

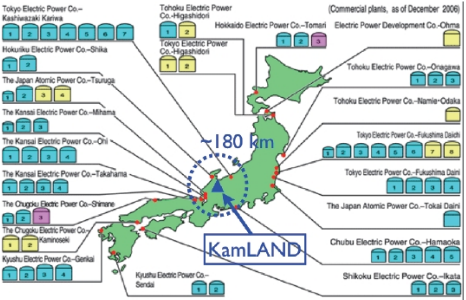




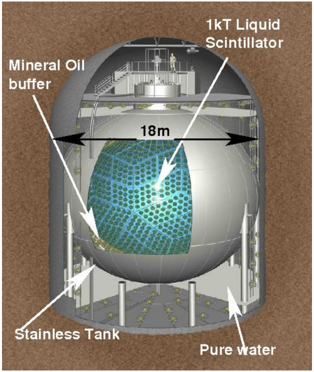
L = 0 to 13,000 km

KamLAND: Reactor $\bar{\nu}_e \longrightarrow \bar{\nu}_e$ Oscillations

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_x) = \sin^2 2\theta_{solar} \sin^2 \frac{1.27\Delta m^2_{solar} L}{E}$$

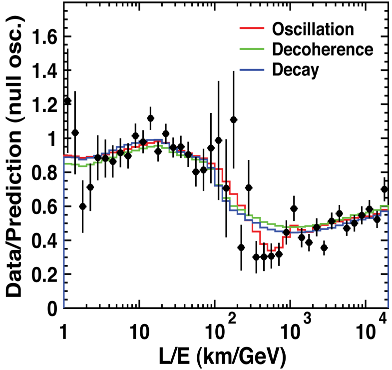


World reactors + Research reactors : 0.96%
Korean reactors : 3.2%

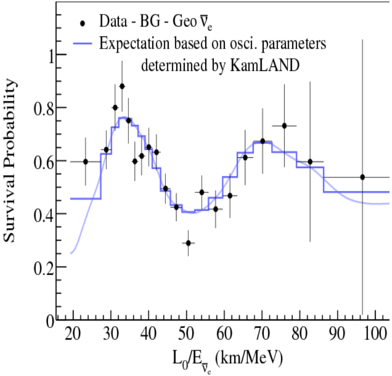


Two Different Mass Scales!

Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ eV^2$$

$$\sin^2\theta_{atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E $\sim$ 500 km/GeV

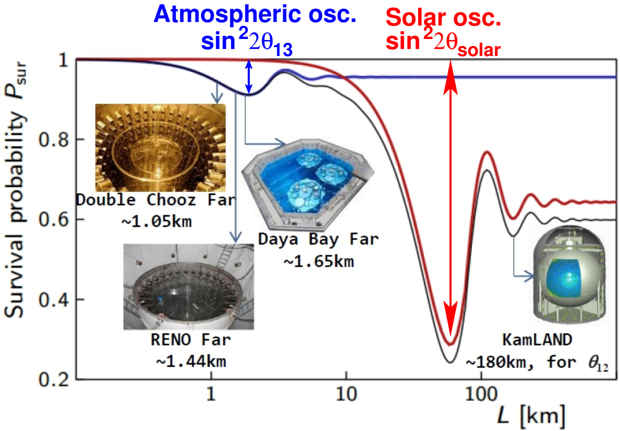
Global fit 2013:

$$\Delta m^2_{solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ eV^2$$

$$\sin^2\theta_{solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E $\sim$ 15,000 km/GeV

More Reactor $\bar{\nu}_e$: The 3rd Mixing Amplitude

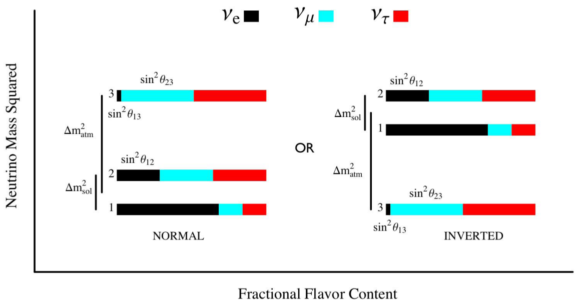


In 2012: Measurement of a 3rd mixing amplitude:

$$\sin^2\theta_{13} = 0.0241 \pm 0.0025$$

Much smaller than $\sin^2\theta_{solar}$ and $\sin^2\theta_{atm}$.

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales, and a CP violating phase

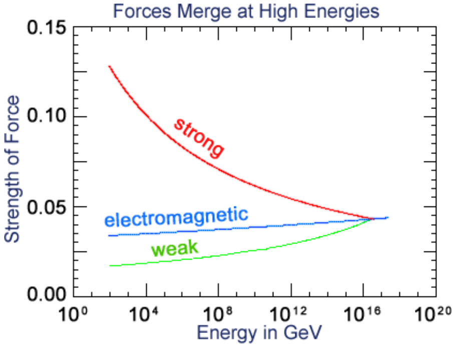


Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12} (solar)	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23} (atm.)	$38 \pm 1^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$
Δm^2_{solar}	$+(7.54 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{atm.}\rvert$	$(2.43^{+0.10}_{-0.06}) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	$-170 \pm 54^\circ$	$67 \pm 5^\circ$

Unknown: Is $m_1 < m_3$ or vice versa?. Whats the value of δ_{cp}?

Neutrino Masses in the Standard Model

In Grand Unified Theories all 3 forces (strong, electro-magnetic, weak) unify at very high energies:



A minimal re-normalizable extension to the Standard Model to account for 3 small left-handed neutrinos introduces 3 additional massive scalar *right-handed* sterile neutrinos of mass $\sim$ M. M $\sim$ GUT scale or M $\sim$ 1 TeV (DARK MATTER?)

See-saw model: Neutrinos are Majorana ($\nu \equiv \bar{\nu}$)

Searching for CP Violation in Neutrino Oscillations

Matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations (or vice versa):.

The charge-parity (CP) asymmetry is defined as

$$\mathcal{A}_{cp} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

$$\mathcal{A}_{cp} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

from Z. Parsa, BNL

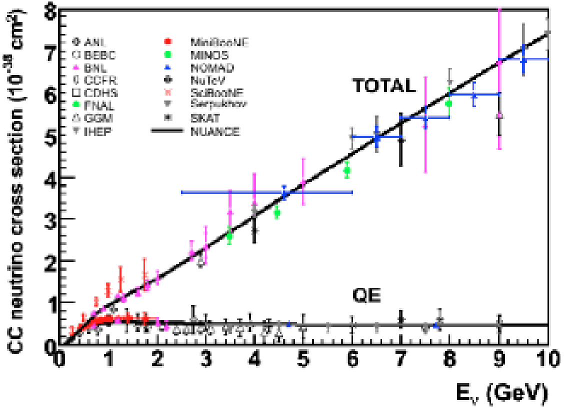
The CP phase δ_{cp} is unknown. CP is violated when $\delta_{cp} \neq 0, \pi$

The 3 most important things to know about ν CPV

- $\mathcal{A}_{cp} \propto 1/\sin\theta_{13} \Rightarrow$ Large θ_{13} makes CPV searches HARDER.
- $\mathcal{A}_{cp} \propto 1/E_\nu \Rightarrow$ CP asymmetries are larger at lower energies
- $\mathcal{A}_{cp} \propto L \Rightarrow$ CP asymmetries are larger at longer baselines

Neutrino Interaction Cross-sections

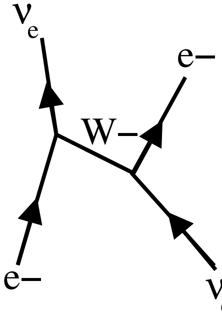
Neutrino CC cross-sections are very small and scale with energy:



Long baseline oscillations over 100's km and $\geq$ 200 MeV energies needed to probe CPV

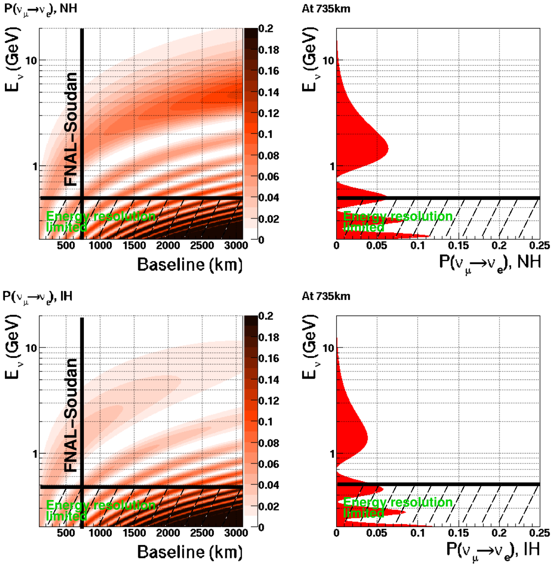
Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter adds a coherent forward scattering amplitude to neutrino oscillation amplitudes. This acts as a refractive index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.

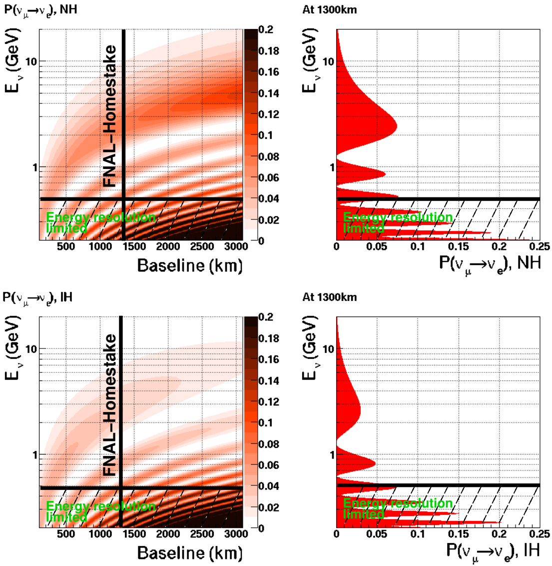


The matter effect on ν_e scattering can be used to detect the unknown neutrino mass ordering using $\nu_x \longrightarrow \nu_e$ oscillations through matter

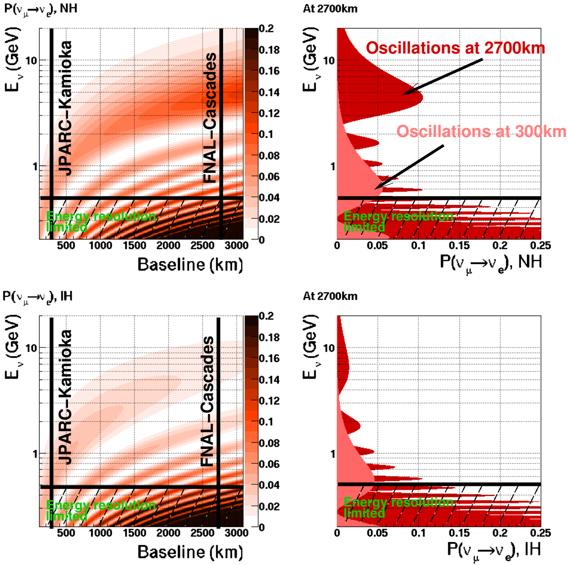
Matter Effect on $\mathbf{P}(\nu_\mu \longrightarrow \nu_e)$



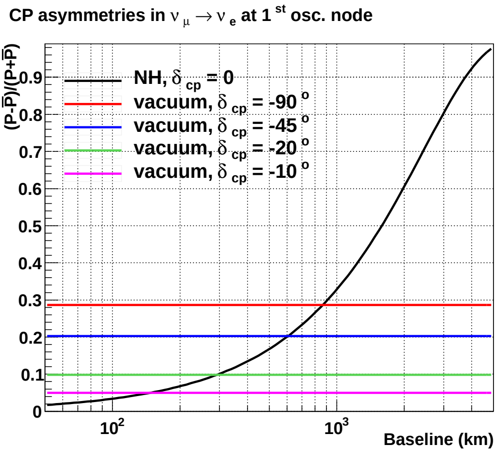
Matter Effect on $P(\nu_\mu \rightarrow \nu_e)$



Matter Effect on $P(\nu_\mu \to \nu_e)$



CP and Matter Asymmetries vs. Baselines for fixed L/E



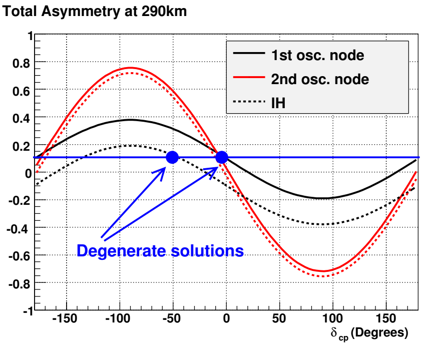
Impact of the mass hierarchy on asymmetry is very large in long baseline experiments

CP Asymmetries and the Mass Hierarchy

$\nu_\mu \rightarrow \nu_e$ **oscillation maxima occur at**

$$E^n_\nu(\mathrm{GeV}) = \frac{2.5\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3\ldots$$

L = 290km



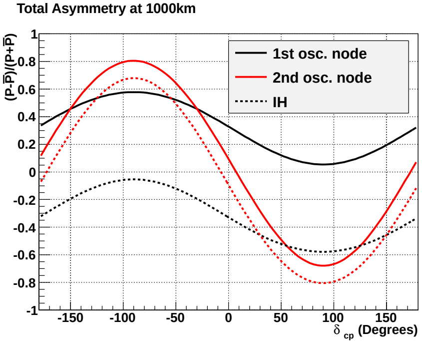
At short baselines, irreducible degeneracies with MH,δ_{cp}

CP Asymmetries and the Mass Hierarchy

$\nu_\mu \rightarrow \nu_e$ **oscillation maxima occur at**

$$E^n_\nu(\mathrm{GeV}) = \frac{2.5\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

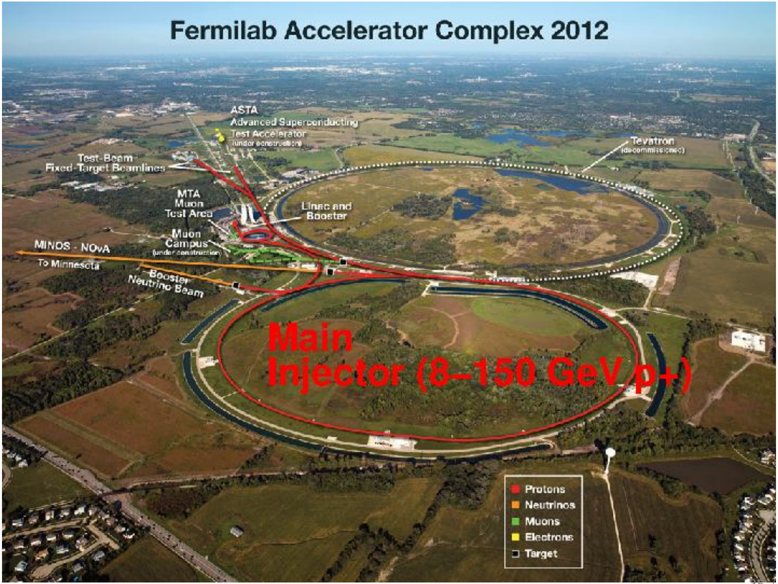
L = 1000km



A baseline > 1000km is needed separate MH from δ_{cp}

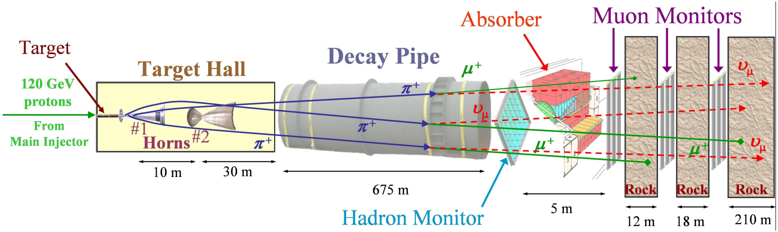
ACCELERATOR ν Experiments

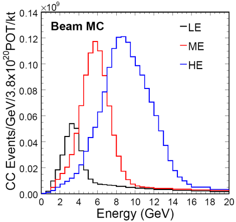
The Fermilab Accelerator Complex 2012

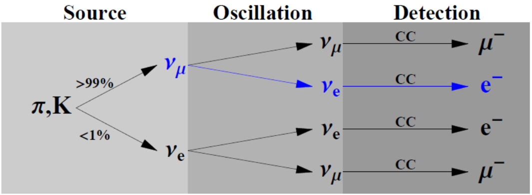


Neutrinos at the Main Injector (NuMI)

High power TUNABLE conventional neutrino beam:



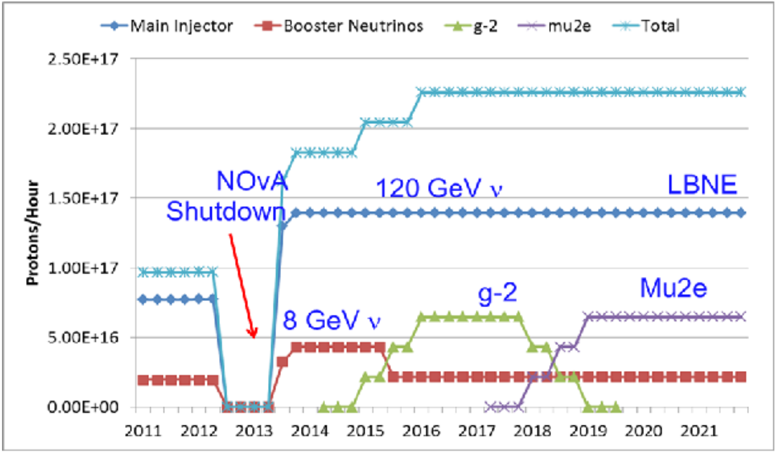




NuMI as built cost (2004): $\sim$ \$115 M (did not include all labor costs!!!)

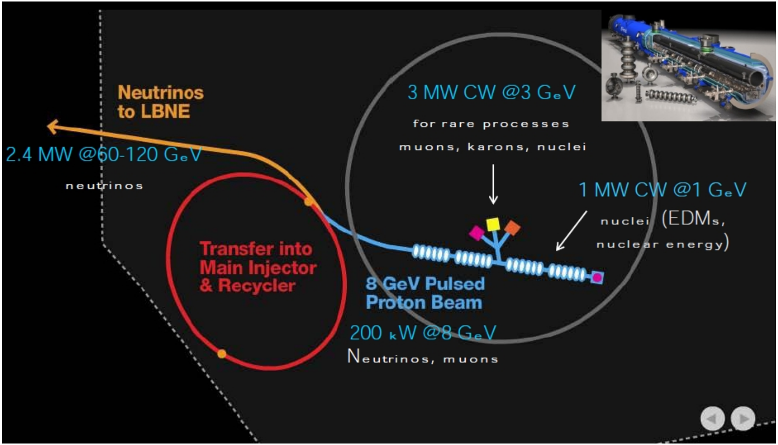
$>3\times$ more expensive in FY12 \$!

Fermilab Proton Plan



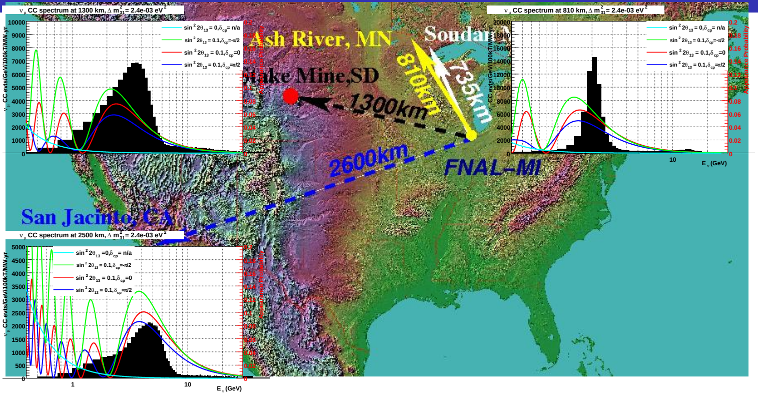
Fermilab proton improvement plan: MI: 700 kW at 120 GeV by 2014

Future plans at Fermilab: Project X



Beyond 2025?: 2.4 MW at 60-120 GeV

Superbeam Baselines in the U.S.

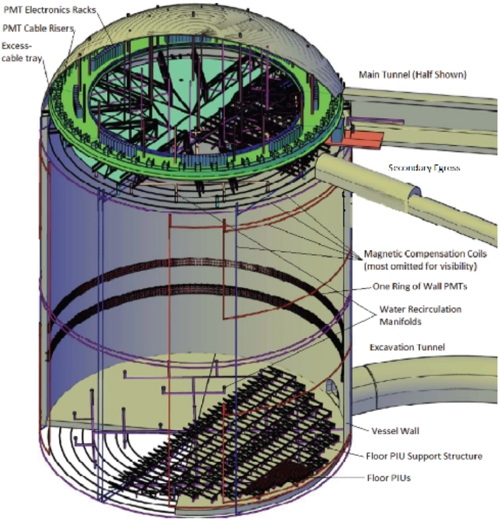


CC event rates per 100kt.MW.yrs (1 MW.yr= 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, NH:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Ash River 810km	18K	7.3K	3.6K	330	710	TBD
Hmstk 1300km	29K	11K	5.0K	280	1100	TBD
CA 2500km	11K	2.9K	1.6K	85	760	TBD

Need MW beams and 100 kton detectors regardless of baseline!

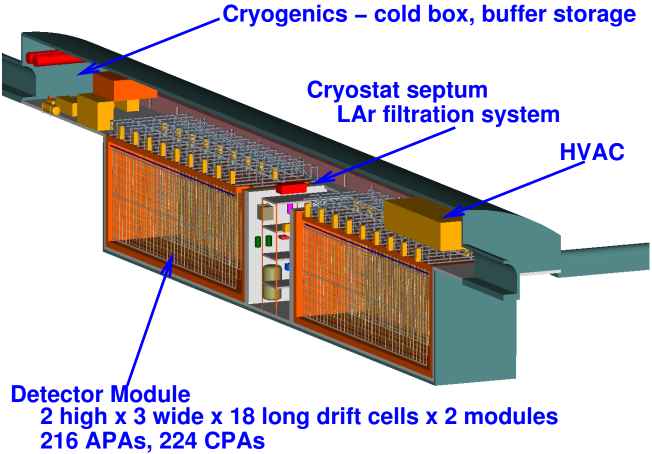
Massive Neutrino Detectors: Water Cherenkov



200kTon (underground) : $\sim$ 700\$M FY10\$ (incl. 40% contingency)

Massive Neutrino Detectors: The LAr TPC

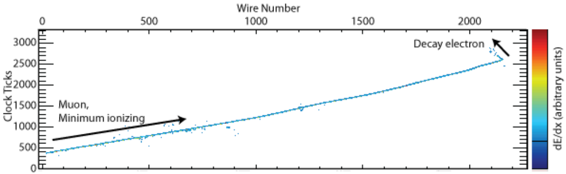
A 35 kton fiducial Liquid Argon Time-Projection-Chamber:



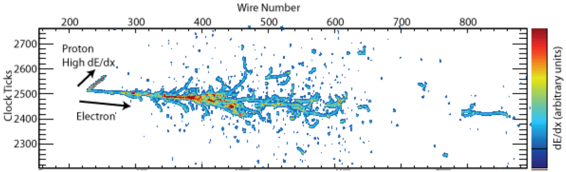
35 kton (underground) : $\sim$ 660\$M FY10\$ (incl. 40% contingency)

Neutrino Interactions in a LAr-TPC

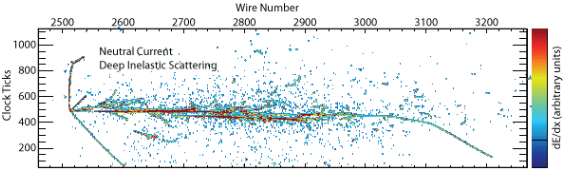
ν_μ CC



ν_e CC



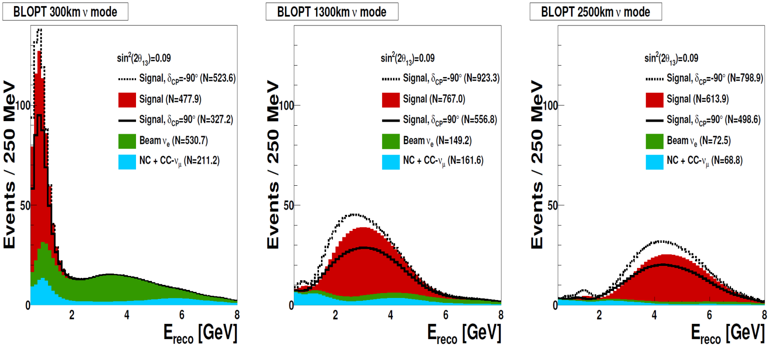
ν_x NC



Sensitivities vs Baseline

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

$\nu_\mu \longrightarrow \nu_e$ Appearance. Normal Hierarchy



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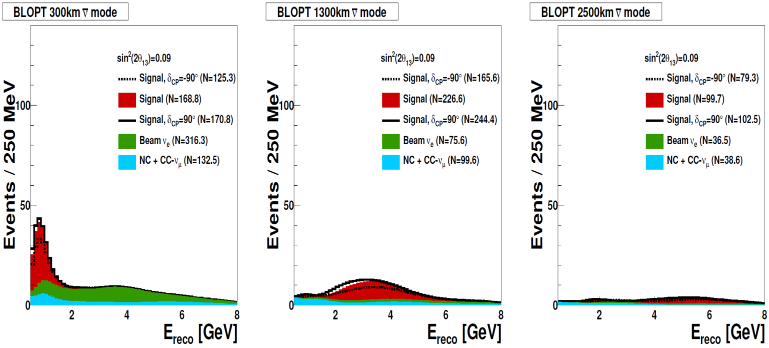
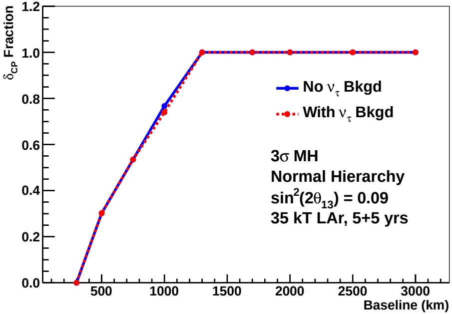


Sensitivities vs Baseline

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

Mass hierarchy senstivity at $\geq 3\sigma$

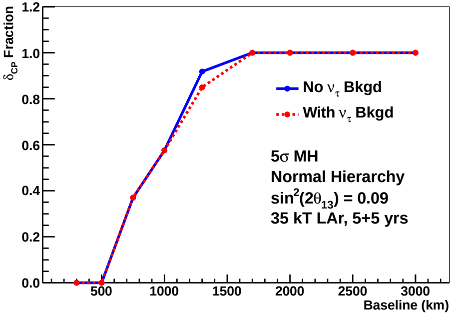


Baselines of 1500-1700km sufficient to resolve MH

Sensitivities vs Baseline

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

Mass hierarchy senstivity at $\geq 5\sigma$

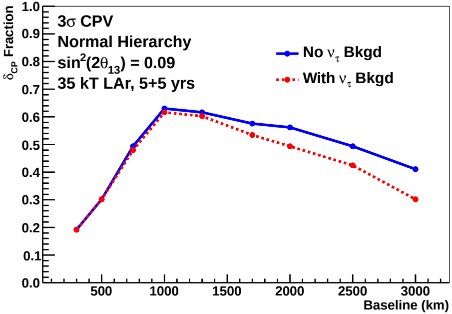


Baselines of 1500-1700km sufficient to resolve MH

Sensitivities vs Baseline

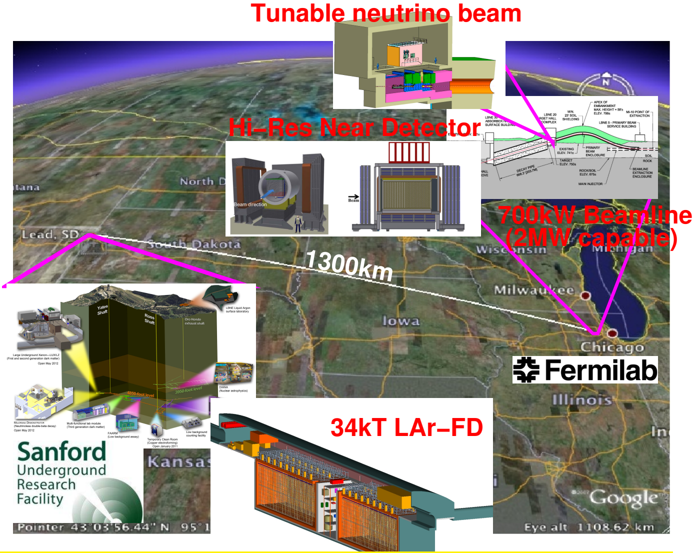
Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

CP violation sensitivity at 3σ



Baselines of 1000-1500km best CPV sensitivity

The Long Baseline Neutrino Experiment



$\sim$ 350 people, 60 institutions from US, India, Italy, Japan, UK

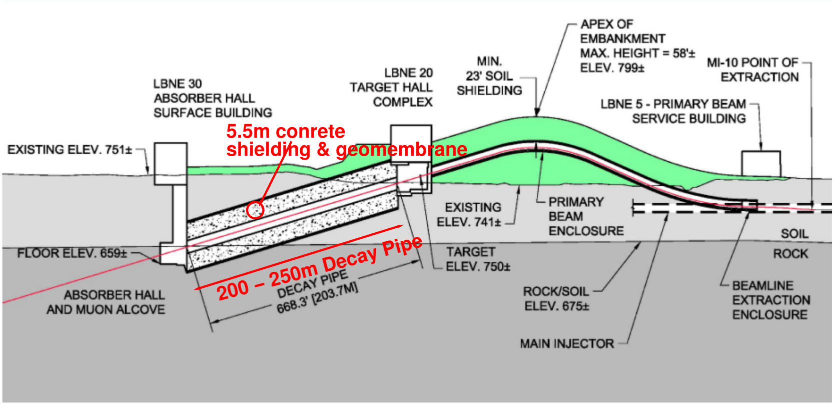
The Sanford Underground Research Facility (SURF)

Dedicated underground research lab at Homestake Mine since 2008

Located 1300km from Fermilab : optimal basline for CPV.

The LBNE Beamline

Novel beam-on-a-hill construction for 2.3MW from 60-120GeV

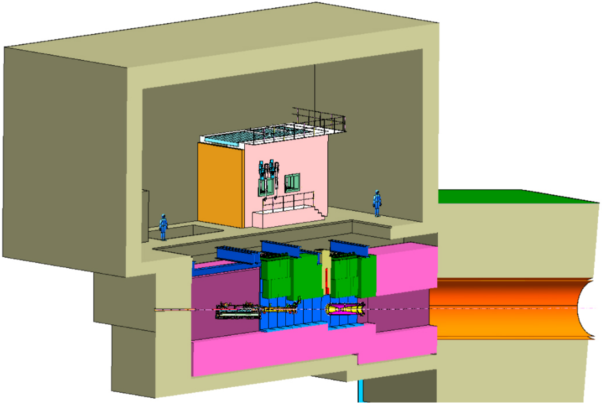


Cost: $\sim$ 390\$M AY (CD1) with 204m decay pipe

(incl 30% cont. and conventional facilities)

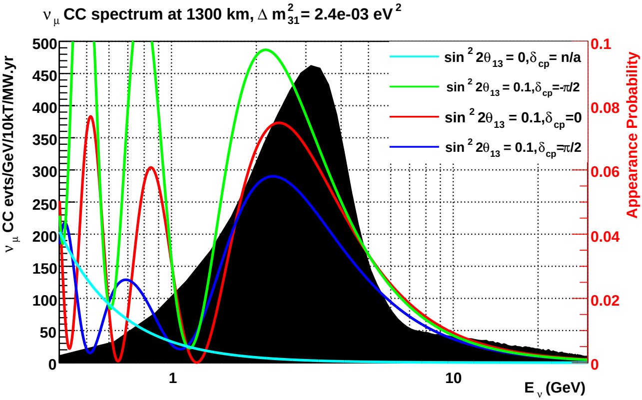
The LBNE Beamline

Utilizes tunable NuMI targetry/focusing designs



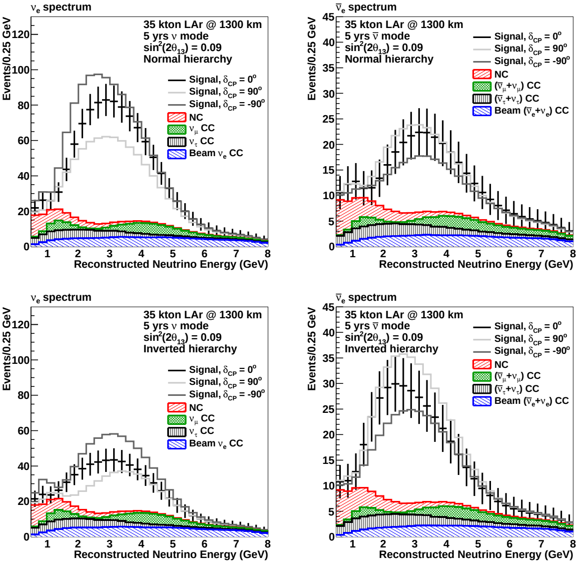
The LBNE Beamline

Excellant match to $\nu_\mu \longrightarrow \nu_e$ oscillation



ν_e Appearance Signals in LBNE 35 kton LAr-TPC

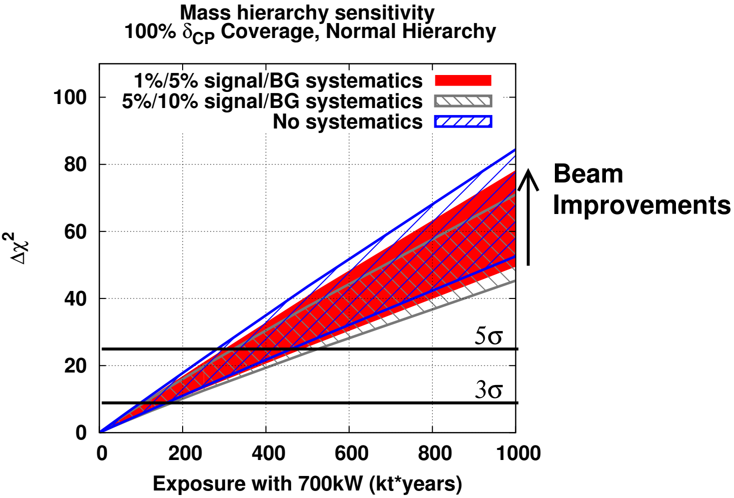
L. whitehead, UH



LBNE MH/CPVSensitivities with 700kW Beam, 35 kton.

M. Bass, CSU

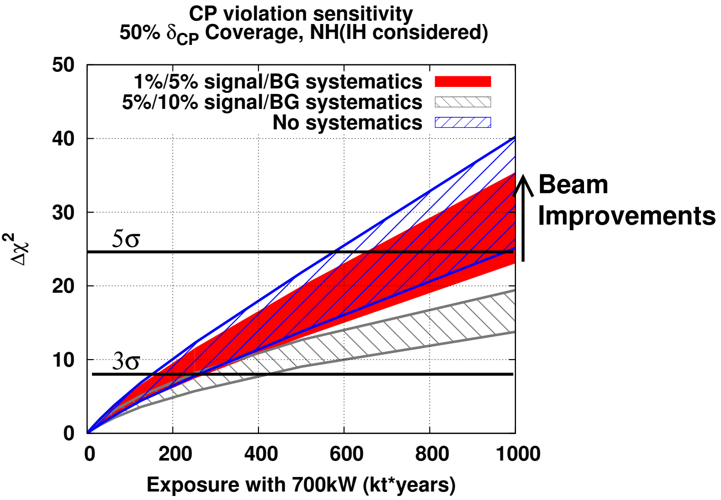
Worst case sensitivity to mass ordering vs exposure



LBNE MH/CPVSensitivities with 700kW Beam, 35 kton.

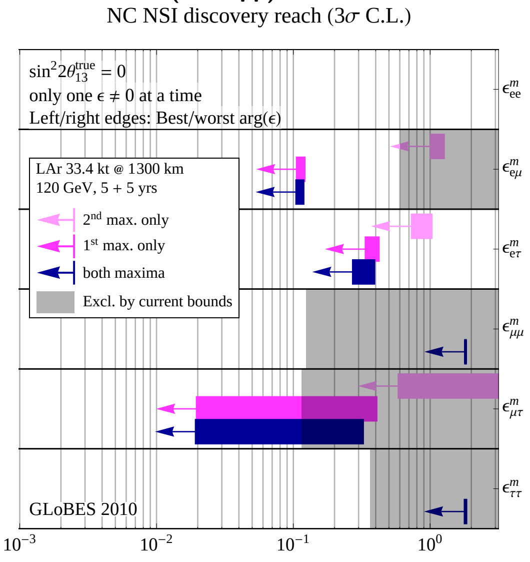
M. Bass, CSU

Worst case CPV sensitivity to 50% of δ_{cp} allowed values:



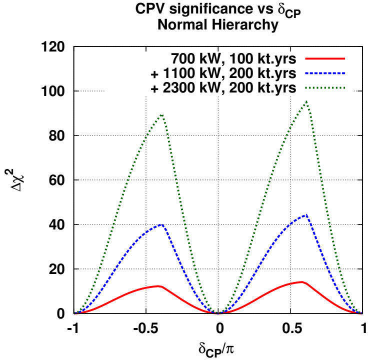
Sensitivity to New Physics, 35kTon, 700kW, 10yrs

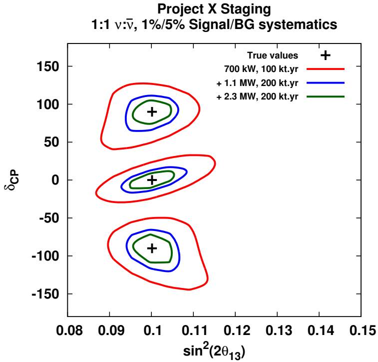
Non-standard interactions (J. Kopp):



CPV with higher power beam from Project X

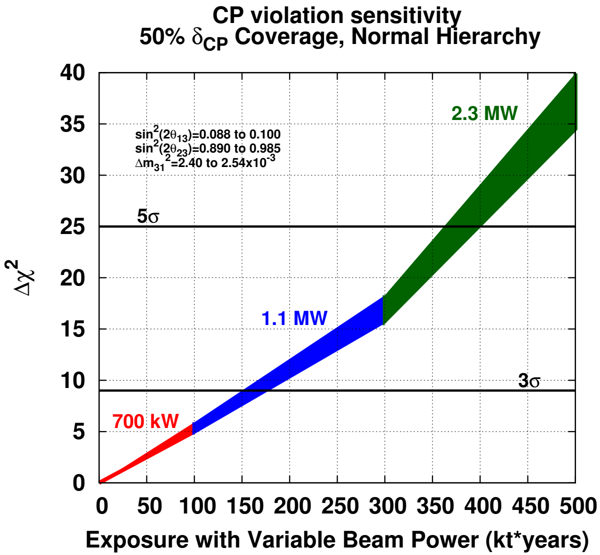
M. Bass, CSU





With sufficient exposure we can reach $5 - 10^\circ$ resolution on δ_{cp}.

CPV with higher power beam from Project X



LBNE Phase I CD1 Approved Project

LBNE recieved DOE CD1 approval for phase I Dec 2012

DOE Goal: Phase I includes ND and $>$ 10 kton underground

by attracting non-DOE contributions.

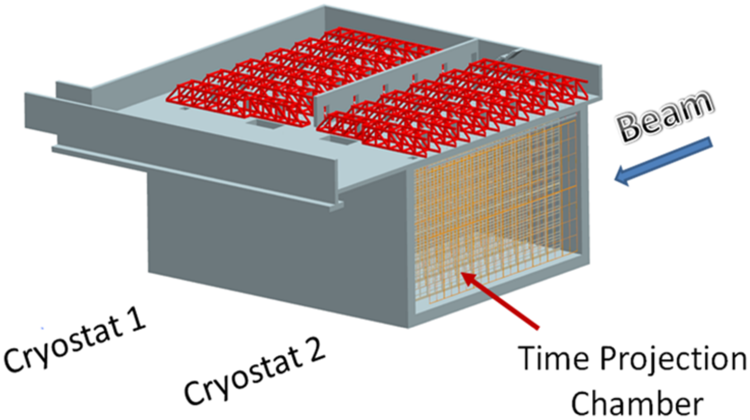
LBNE CD1 Costs

J. Strait

LBNE Cost Estimate in At-Year k$	Base Cost k$	Contingency		TPC k$	cost to date thru 6/2012
		k$	% of cost to go		
130.01 Proj Office	57,014	16,099	32%	73,113	6,987
130.02 Beamline	129,370	35,311	29%	164,680	7,422
130.03 NDC	11,815	10,748	148%	22,563	4,558
130.04 WCD	11,178		0%	11,178	11,178
130.05 LAr FD	181,347	71,767	41%	253,114	7,775
130.06 CF	241,191	71,600	31%	312,790	6,872
Top-down Contingency		30,000	5%	30,000	
Grand Total	**631,914**	**235,525**	**40%**	**867,439**	**44,792**

Phase I: 10 kton LAr-TPC at SURF

10 kT Liquid Argon TPC for the LBNE Experiment:

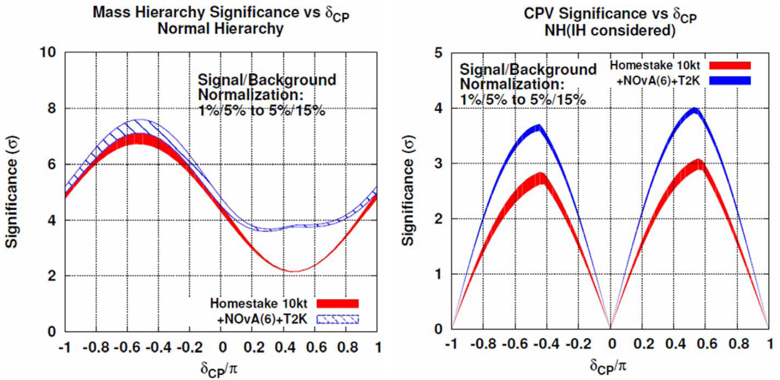


Cost: $\sim$ 260 \$ M AY (incl 40% cont, no CF), Ready 2022

Extra cost to go underground: $\sim$ 135 M\$

Phase I Mass Hierarchy/CP Violation Sensitivity

M. Bass, CSU



The mass hierarchy can be determined using LBNE I+ T2K/NOνA

LBNE I + T2K/NOνA $\Rightarrow \geq 3\sigma$ sensitivity to CPV for 35% of δ_{cp}

SUMMARY AND CONCLUSIONS

Summary

The 3 flavor framework for neutrino oscillations is well established

- **Experiments have identified 2 very different mass scales and 3 mixing amplitudes.**
- **The mass ordering (hierarchy) of the 1 and 3 mass states is still unknown.**
- **The measurement of the hierachy using the matter effect in long baseline accelerator $\nu_\mu \rightarrow \nu_e$ is the most effective technique.**
  MH determination in LB ν is independent of detector systematics
- **Discovering ν CPV requires many 100kt .MW .yr exposures!**
- **While it is NOT necessary to know MH to measure CP violation.**
  Baselines of $>$ 1000 km are needed to cleanly separate CP violating effects from matter effects.
- *The LBNE experiment has the 1) optimal baseline, 2) multi-MW beam design and 3) best detector technology*. **LBNE phase I preserves all 3 features. Extra non-DOE funding to increase phase I detector size, go underground, and add a near detector are being sought.**

Thank you